Atmospheric Effects of Stratospheric Aircraft

An Evaluation of NASA's Interim Assessment

Panel on Atmospheric Effects of Stratospheric Aircraft
Committee on Atmospheric Chemistry
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1994

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This material is based on work supported by the National Aeronautics and Space Administration under Contract Number NASW-4003.

Cover art:

BOCCIONI, Umberto.
The City Rises. (1910).
Oil on canvas, 6'61/2" x 9'101/2".
The Museum of Modern Art, New York. Mrs. Simon Guggenheim Fund.
Photograph © 1993 The Museum of Modern Art, New York.

A limited number of copies of this report are available from the Board on Atmospheric Sciences and Climate, National Research Council, 2101 Constitution Avenue, N.W., Washington, DC 20418

Printed in the United States of America

PANEL ON ATMOSPHERIC EFFECTS OF STRATOSPHERIC AIRCRAFT

THOMAS E. GRAEDEL (*Chairman*), AT&T Bell Laboratories, Murray Hill, New Jersey
DANIEL CARIOLLE, Centre National de Recherches Météorologiques, Toulouse
MARVIN A. GELLER, State University of New York, Stony Brook
JACK L. KERREBROCK, Massachusetts Institute of Technology, Cambridge
DAVID H. LISTER, Defence Research Agency, Farnborough, U.K.
KONRAD MAUERSBERGER, University of Minnesota, Minneapolis
STUART A. PENKETT, University of East Anglia, Norwich, U.K.
ULRICH SCHMIDT, Institut für Chemie und Dynamik der Geosphare, Forschungszentrum Jülich GmbH, Jülich, Germany
STEPHEN E. SCHWARTZ, Brookhaven National Laboratory, Upton, New York
SUSAN SOLOMON, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Boulder, Colorado

Staff

WILLIAM A. SPRIGG, Director
DORIS BOUADJEMI, Administrative Assistant
ELLEN F. RICE, Editor

COMMITTEE ON ATMOSPHERIC CHEMISTRY

WILLIAM L. CHAMEIDES (*Chairman*), Georgia Institute of Technology, Atlanta
JAMES G. ANDERSON, Harvard University, Cambridge, Massachusetts
MARY ANNE CARROLL, University of Michigan, Ann Arbor
JEREMY M. HALES, Consultant, Kennewick, Washington
DAVID J. HOFMANN, NOAA Environmental Research Laboratories, Boulder, Colorado
BARRY J. HUEBERT, University of Hawaii, Honolulu
JENNIFER ANN LOGAN, Harvard University, Cambridge, Massachusetts
PAMELA ANNE MATSON, NASA Ames Research Center, Moffett Field, California
MARIO J. MOLINA, Massachusetts Institute of Technology, Cambridge
A. R. RAVISHANKARA, NOAA Aeronomy Laboratory, Boulder, Colorado

Staff

WILLIAM A. SPRIGG, Director
DAVID SLADE, Senior Program Officer
DORIS BOUADJEMI, Administrative Assistant
THERESA M. FISHER, Administrative Assistant

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

JOHN A. DUTTON (*Chairman*), Pennsylvania State University, University Park
E. ANN BERMAN, International Technology Corp., Edison, New Jersey
CRAIG E. DORMAN, Consultant, Arlington, Virginia
MICHAEL FOX-RABINOVITZ, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
THOMAS E. GRAEDEL, AT&T Bell Laboratories, Murray Hill, New Jersey
ISAAC M. HELD, National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey
WITOLD F. KRAJEWSKI, University of Iowa, Iowa City
MARGARET A. LeMONE, National Center for Atmospheric Research, Boulder, Colorado
DOUGLAS K. LILLY, University of Oklahoma, Norman
RICHARD S. LINDZEN, Massachusetts Institute of Technology, Cambridge
GERALD R. NORTH, Texas A&M University, College Station
EUGENE M. RASMUSSON, University of Maryland, College Park
JOANNE SIMPSON, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
GRAEME L. STEPHENS, Colorado State University, Fort Collins

Ex Officio Members

ERIC J. BARRON, Pennsylvania State University, University Park
WILLIAM L. CHAMEIDES, Georgia Institute of Technology, Atlanta
MARVIN A. GELLER, State University of New York, Stony Brook
PETER V. HOBBS, University of Washington, Seattle

Staff

WILLIAM A. SPRIGG, Director
MARK HANDEL, Senior Program Officer
DAVID H. SLADE, Senior Program Officer
DORIS BOUADJEMI, Administrative Assistant
THERESA M. FISHER, Administrative Assistant
ELLEN F. RICE, Editor

COMMISSION ON GEOSCIENCES, ENVIRONMENT, AND RESOURCES

Preface

The advent of high-speed civil transport aircraft (HSCTs) some 25 years ago generated considerable concern about potential impacts on the stratosphere. With interest in such aircraft again increasing, the National Aeronautics and Space Administration initiated an assessment of the potential stratospheric impacts of a substantial increase in the use of HSCTs. This assessment was intended to examine, from the standpoint of present scientific understanding, the potential atmospheric impacts of a fleet of high-speed civil transports flying supersonically in the lower stratosphere. The program was initiated in 1991, and the bulk of its research is scheduled to be completed in 1995, although it may be extended. In early 1993 NASA asked the National Research Council to review its efforts.

The panel established by the NRC Board on Atmospheric Sciences and Climate (BASC) was requested to ascertain whether key uncertainties had been identified, and whether the NASA program would reduce those uncertainties sufficiently that policies regarding environmental constraints on high-speed transports could be formulated. To this end, the panel was asked to evaluate whether the present state of knowledge was accurately reflected in a 1993 NASA interim report on the assessment program, and to identify any additional research that should be conducted before 1995, or thereafter, to reduce these uncertainties. At NASA's request, the independent technical review presented in this document provides both an evaluation of the quality and completeness of the research program and recommendations for improvements.

The potential stratospheric impacts of aircraft were addressed in some detail in the early 1970s by the U.S. Department of Transportation under the Climatic Impact Assessment Program (CIAP). One conclusion of CIAP was that stratospheric ozone might be highly vulnerable to exhaust from aircraft engines. Controversy surrounding this conclusion, along with the recognition that substantial depletion of stratospheric ozone would represent a serious environmental concern, were among the factors that discouraged the United States from developing supersonic transport aircraft. Now a new understanding of stratospheric dynamics and chemistry flowing from continued research, advances in aircraft technology, and a perception that significant markets exist for HSCTs all encourage a re-examination of the issue. The NASA study being reviewed here is thus timely and appropriate.

The panel expresses its appreciation to the NASA program administrators and participating scientists for their cooperation. Information was shared fully with the panel, and special efforts were made by NASA to provide informative reviews for the panel's use. In particular, Mr. Howard L. Wesoky, Dr. Richard S. Stolarski, Dr. Robert T. Watson, and Ms. Kathy A. Wolfe were very helpful. Moreover, the panel greatly appreciates the assistance of the BASC staff, including Mrs. Doris E. Bouadjemi, Ms. Ellen F. Rice, and Dr. William A. Sprigg.

John A. Dutton, Chairman
Board on Atmospheric Sciences and Climate

Contents

Executive Summary

The development of a fleet of high-speed civil transport (HSCT) aircraft for stratospheric flight is being given serious consideration by the aeronautics community, as it appears that such aircraft may be not only technologically feasible but also economically advantageous. The financial considerations in such a program involve major commitments by industry, however; sales estimates as high as $100 billion for a fleet of approximately 500 aircraft have been made. To investigate the scientific and technological considerations involved before such large sums are committed, NASA has established the High-Speed Research Program (HSRP), elements of which include engine and airframe conceptual development, and materials science.

A major concern about the development and operation of a fleet of supersonic aircraft is the prediction of its possible environmental consequences. The principal atmospheric impacts are expected to be ozone depletion and/or redistribution, and climate effects. For the purpose of assessing the degree to which concern over those impacts is warranted, NASA has established as part of HSRP a program of research on the atmospheric effects of stratospheric aircraft, AESA. It is this effort that is the subject of the present evaluation.

The approach taken by AESA—indeed, the only approach likely to provide a reasonable assessment of HSCT impacts—has been to employ atmospheric chemical models to calculate the possible perturbations. Those complex models require much conceptual and factual information in their formulation and operation, so AESA has supported certain observational and laboratory studies in addition to the computer model work.

To provide an independent evaluation of how well the AESA program is meeting the needs for which it was created, NASA requested the National Academy of Sciences' National Research Council (NRC) to establish a review panel in January 1993. The NRC Panel on the Atmospheric Effects of Stratospheric Aircraft was asked to review the AESA Interim Assessment report (and additional relevant information that was made available) and to respond to five questions. In addressing those questions, the panel performed a review of important components of the program; the most important conclusions are summarized below.

HSCT EMISSIONS AND PLUME PROCESSING

Aircraft operational and emission scenarios are crucial to model calculations investigating the effects of HSCTs. The construction of such scenarios has been a major part of the AESA program. AESA has done an excellent job in constructing those scenarios for NO_x and some other major emissions. The panel recommends that similar scenarios be constructed for sulfur dioxide and soot (particulate carbon), a modest task now that the initial scenario work has been completed.

The immediate effect of HSCT emissions on the atmosphere in the wake and extended region behind the aircraft must be described by a plume/wake model. This effort is an important part of AESA's research program. The panel recommends that additional, independent studies of plume/wake processes be carried out so as to avoid conclusions based solely on the results of one research group.

HOMOGENEOUS AND HETEROGENEOUS CHEMISTRY

Progress in laboratory chemistry sponsored by AESA has been very impressive, particularly in the area of chemical reactions on surrogate aerosol surfaces. The panel recommends that further laboratory studies expand the range of species to include sulfur dioxide and the principal organic molecules likely to occur in HSCT emissions, and explore non-equilibrium conditions responsible for solid particle formation.

OBSERVATIONS

The field measurements programs in which AESA has participated have been meritorious, providing unprecedented information on O_3, ClO, BrO, OH, HO_2, and related species. This is a substantial achievement that will add considerable confidence to the predictions of computer models. In the near term, detailed analyses of this and all other relevant data are a high priority. The panel recommends that future field programs emphasize other species important for AESA and thus far not well characterized, such as the composition and morphology of stratospheric aerosol particles and the concentrations of the reservoir molecules N_2O_5 and $ClONO_2$. In some cases, support of instrument development will be required. From the standpoint of geographical location, a northern high-latitude summer campaign should have precedence over other observational options.

TRANSPORT AND DYNAMICS

Once exhaust emissions from HSCT aircraft are dispersed out of the aircraft wake, their subsequent chemical evolution will be governed in major ways by atmospheric transport, especially within flight corridors and just above the tropopause. AESA has relied largely on previous understanding of these processes for its modeling work, but such understanding may be insufficient for spatially distinct HSCT scenarios. The panel recommends that 3-D models be used in addition to the current 2-D ones to evaluate the build-up of aircraft effluents, that aircraft and Earth satellite data (especially on the Mt. Pinatubo eruption) be employed in efforts to increase the understanding of transport in critical atmospheric regions, and that longer-term field programs consider making observations designed to improve knowledge of transport and dynamics in HSCT flight corridors.

MODELING

Computer models for the assessment of atmospheric effects of stratospheric aircraft have been extensively supported by AESA. The scientists who have participated in these tasks have completed a large series of interim assessment calculations, including heterogeneous reactions in their model formulations, and have compared the results of several modeling efforts with each other. Much remains to be done by 1995, however. Increased 3-D modeling should have a high priority, as 3-D results constrain many of the 2-D modeling approaches. The panel recommends that not only comparative 2-D model results but also the reasons for differences be addressed, that parametric sensitivity studies be initiated to attempt to encompass any "surprise" scenarios that may arise, that the implications of modified tropospheric chemistry (including organic chemistry) be addressed, that more extensive comparisons of model results with all applicable data be accomplished, and that new efforts in modeling microphysical aerosol processes be initiated to guide parameterization in larger-scale models.

OTHER TOPICS OF IMPORTANCE

The eruption of Mt. Pinatubo in 1991 has provided, in addition to possible data for assessing transport, a potential test case for the influence of equatorial and midlatitude stratospheric aerosols on chemistry at HSCT flight altitudes and geographical locations. The panel recommends an extensive, coordinated analysis of the evolution of the Mt. Pinatubo aerosol cloud with the object of calibrating chemical models and sensitivity studies within the AESA program.

It is well within the realm of possibility that an HSCT fleet might have deleterious impacts on climate through perturbations in water vapor and additional cloud formation, generation of new aerosol particles, and changes in the vertical distribution of ozone that might even result in altering the altitude of the tropopause. AESA has not yet addressed climate modifications as part of its program, although it acknowledges the need to do so. The panel recommends that the nature and magnitude of potential HSCT-related climatic changes be promptly and carefully evaluated.

PROGRAM MANAGEMENT

AESA, as an applied science program, has the responsibility of providing an assessment of the potential atmospheric impact of an HSCT fleet that is not only credible but also timely enough to offer maximum guidance to the aeronautics community. Fulfilling this mission requires that AESA objectives be clearly established, that program elements be related directly to those objectives, that progress be actively monitored, and that the program be modified if needed. AESA has supported research that is of great intrinsic merit and contributes substantially to the general understanding of atmospheric processes. The panel feels, however, that significant portions of the work have not been directed toward specific AESA needs, resulting in overexploration of some HSCT topical areas and insufficient attention to others. The panel recommends that specific scientific goals be established and widely disseminated within the HSRP/AESA community, that scientists be sought to address critical areas of research for which suitable proposals have not been forthcoming, and that goal realization and monitoring be explicitly included as aspects of program management. To accomplish these tasks, it recommends an increase in hands-on guidance and coordination by the Program Scientist, perhaps requiring the expansion of this position to full time, and a change in the role of the Science Advisory Committee to that of a Scientific Steering Committee charged with more active program oversight.

Finally, on the basis of discussion throughout this report, the panel responds specifically to the five questions in its original charge as follows:

1. **Does the 1993 NASA HSRP/AESA Assessment accurately reflect the current state of scientific knowledge pertinent to HSCTs?**

Yes, on the whole, and in several areas AESA can rightly claim to have markedly enhanced the general understanding of atmospheric chemistry. However, some relevant information external to the program has not been incorporated into the perspectives and analyses of AESA, such as data from orbiting satellite platforms and European in-flight aircraft emissions. The potential for ozone depletion and related climate effects arising from the injection of aerosol particles from stratospheric aircraft also needs to be more extensively explored.

2. **Have the key scientific uncertainties relevant to the atmospheric effects of stratospheric aircraft been identified?**

To answer this question, the panel first compiled its own list of key uncertainties. In the opinion of the panel, the top three key uncertainties are:

- Dispersion of HSCT emissions in the stratosphere
- Physical and chemical properties of stratospheric aerosols and their precursors
- The climate effects of the HSCT fleet.

Also important, but perhaps less crucial, are the following five areas:

- HSCT operational scenarios and the magnitudes of their associated emissions levels
- Plume and wake microphysics and chemistry
- The adequacy of 2-D models for HSCT assessment (essentially a 3-D problem)
- The specification and accomplishment of model sensitivity studies
- Threshold effects and other areas that might harbor surprises.

The only items in the above list that appeared in the original AESA Research Announcement were emissions, climate, and plume/wake processes. The lists of current and projected key uncertainties provided by the Program Manager at the request of the panel include dispersion, 2-D models, and possible surprises. The rapid progress in atmospheric science makes it reasonable that such evolution in the definition of key uncertainties should occur. In the opinion of the panel, however, gas-phase atmospheric chemistry measurements have been overemphasized, whereas aerosol particle observations and their interpretation, studies of dispersion, investigation of potential alteration in the atmosphere's thermal balance, and most particularly model sensitivity studies should have been identified as key research elements early in the program, and should have remained so.

3. **Is the NASA/AESA program appropriately designed, within funding constraints, to reduce the key uncertainties?**

In many cases, but not all. Many of the AESA program elements have definitely contributed to a reduction in key uncertainties. However, the program goals, as well as the plans for monitoring progress toward those goals, have sometimes not been completely clear. As a result, the allocation of funds has at times been inconsistent with the AESA key uncertainties. For example, significant AESA funds were committed to the Perseus program, which will yield most of its results beyond AESA's 1993-1995 time frame, rather than to detailed analysis of already existing relevant data, such as Upper Atmosphere Research Satellite measurements of the global distribution of aerosols and long-lived tracers.

4. **Are there major research activities currently not funded that would likely reduce the scientific uncertainties before 1995?**

The broad subjects being funded by AESA (modeling, field observations, laboratory studies, emissions assessment) are clearly appropriate for the task of reducing scientific uncertainties. In the view of the panel, however, some changes in funding structure and emphasis appear advisable. Among those for which the panel recommends augmentation of effort are:

- Three-dimensional chemical assessments, with more attention to incorporating data from satellites
- Parameter space sensitivity studies in 2-D models
- Examination of HSCT effects on climate, especially those pertaining to water vapor and ozone
- Organic chemistry in the upper troposphere
- Additional, independent studies of plume/wake processes

Not enough time is available before AESA is scheduled to end to permit substantive changes to be implemented in the observational measurement program. However, it would be advisable to place greater emphasis on modeling and interpretation of data already in hand, specifically on HSRP issues.

5. **Will major scientific uncertainties remain after 1995? If so, what types of research efforts could significantly reduce those uncertainties within a few years?**

Further research in the post-1995 time frame will clearly increase the level of confidence of any subsequent assessments. The panel recommends attention to five specific areas in the post-1995 time frame:

- Long-term, systematic monitoring that integrates in situ measurements, satellite observations, and 3-D model assimilations with the specific goal of improving understanding of stratosphere-troposphere exchanges

- Increased use of 3-D models to assess ozone depletion and climate changes, including both sensitivity studies and intercomparisons of model performances and differences
- Measurements in aircraft wakes, flight corridors, and, where appropriate, wind tunnels to validate plume/wake and mesoscale models
- A high-latitude summer aircraft field program, emphasizing condensed-phase species
- The use of microphysical models for studies of aerosol particle formation, phase transitions, and particle size distribution evolution.

In addition, the panel encourages AESA to forge strong cooperative links with other relevant programs, particularly the NASA program on effects of subsonic aircraft now beginning, as long as those cooperative efforts do not dilute the progress of AESA toward its own particular goals.

1

Introduction

The ever-increasing pace of globalization has brought with it renewed interest in faster civil transport aircraft. Recent studies by the National Aeronautics and Space Administration (NASA) and others have indicated that modern technology and engineering approaches are capable of designing and building high-speed civil transports (HSCTs) that are economically advantageous. This realization, together with the obvious international implications of such an effort, resulted in NASA's setting up programs in the late 1980s to address technology issues that required resolution before such aircraft were designed. At the same time, programs were established to deal with concerns regarding community noise, sonic booms, and atmospheric impacts. The last of these topics is perhaps the greatest potential impediment to flying the HSCTs, since these atmospheric impacts may be very difficult to predict accurately. Thus, the Atmospheric Effects of Stratospheric Aircraft (AESA) segment of NASA's High-Speed Research Program (HSRP) is of great importance, and its conclusions (and their likely reliability) are of considerable interest, particularly to manufacturers. AESA may continue beyond 1995, but it has already produced several summaries of its scientific activities, including the 1993 interim assessment that is the primary focus of this report.

SCIENTIFIC ISSUES RELATED TO ATMOSPHERIC EFFECTS OF STRATOSPHERIC AIRCRAFT

Concerns regarding the influence of stratospheric aircraft emissions on the atmosphere were first raised in the 1970s. The primary atmospheric focus at that time was the effect of emissions on stratospheric ozone concentrations, because ozone is susceptible to catalytic decomposition by gases present in very small concentrations. The most common catalytic cycle can be expressed as

$$XO + O_3 \rightarrow XO_2 + O_2$$
$$XO_2 + O \rightarrow XO + O_2$$
$$\text{Net:} \quad O_3 + O \rightarrow 2O_2$$

where X can be N or H (among others). The concern with respect to stratospheric aircraft was that water vapor (a precursor to HO) and NO_x ($NO + NO_2$) are emitted from jet aircraft engines. This concern continues today with respect to a prospective HSCT fleet. Specific features of aircraft influences on ozone include changes in total column abundance (important to penetration of ultraviolet radiation), modification of vertical concentration profile (important to the temperature structure of the atmosphere), and the geographical and temporal variability of these properties.

In addition to NO_x and water vapor, jet aircraft engines also emit CO_2, CO, soot, sulfur gases, various types of organic molecules, and other trace constituents. This ensemble of species may have the potential not only to perturb ozone but also to induce climate change through, for example, increased cloud extent, added aerosol particles (sulfur-containing gas, soot), and added infrared-absorbing molecules (e.g., H_2O).

An initial assessment of the potential atmospheric effects of HSCT may be made by comparing estimates of the concentrations of effluents that will result from fleet operations with the ambient background concentrations. This is done in Table 1 on page 11 of the Interim Assessment. That table indicates increases in NO_x (up to 250 percent), H_2O (up to 40 percent), SO_x (up to 40 percent), H_2SO_4 (up to 200 percent), soot (up to 100 percent), and CO (up to 20 percent). These comparisons, all for a "broad corridor at northern midlatitudes," demonstrate the need for a detailed assessment of possible HSCT influences on the atmosphere.

Whether significant effects on ozone or climate will occur as a consequence of emissions from a fleet of supersonic aircraft depends on many different factors, including the rate of emissions from a single aircraft, the size of the aircraft fleet, the geographical and altitudinal distribution of the emissions, the rapidity and efficiency with which those emissions are mixed into the general atmosphere, the chemical composition of the fuel, and the chemical and physical transformations. The emission rates from engines characteristic of potential HSCT aircraft obviously cannot be measured, since the engines have not yet been built. Similarly, the atmospheric effects resulting from a given prospective scenario of emissions cannot be measured directly. Thus, detailed predictions of atmospheric effects must be made using computer simulation models. In order to obtain realistic predictions with these models, one must bracket reasonable projections of emissions with a combination of historical emission experience and new engine design concepts. Furthermore, the models require specification of the atmospheric radiation field, chemical-reaction and phase-transformation parameters, atmospheric transport, and so forth.

THE HSRP/AESA PROGRAM

The AESA component of the NASA HSRP began in FY 1990 and has an approved budget plan through FY 1995. Its charge (as interpreted by the panel authoring this report) is *to lay the knowledge base that will allow intelligent decisions to be made on acceptable emission rates and fleet operations for HSCTs.* HSRP and its components, including AESA, need to produce robust and reliable results if HSCTs are to be built, since the potential engine and airframe expense is very great; the potential rewards are also great, however—perhaps $100 billion in sales for a fleet of approximately 500 aircraft.

AESA activities have been guided by a NASA Program Manager and by Program Scientists, in consultation with a distinguished Scientific Advisory Panel drawn mainly from the community of atmospheric scientists. The research that has been performed has included field and laboratory measurements, model-related theoretical studies, and computer model assessments. A number of these activities have been performed in conjunction with NASA's Upper Atmosphere Research Program (UARP) and Atmospheric Chemistry Modeling and Analysis Program (ACMAP).

It is important to put the scale of AESA activities into perspective vis-à-vis other related programs. The overall HSRP budget has been about $70 million per year, most of which is directed toward studies of aircraft and engine technology and materials. Within this program, AESA's annual budget is about $6 million for FY 1990 through FY 1995, or a total of about $36 million. In contrast, UARP's annual budget during that time period has averaged $20 million; ACMAP's, $6 million. Thus, the AESA program exists in an environment that includes the related research of the UARP and ACMAP programs, and is building on a research and knowledge base that is much greater than could be afforded by AESA alone. In the judgment of the panel, reliance on this research and knowledge base is appropriate and indeed crucial to the success of the program. However, there is potential for compromising the objectives of AESA through, for example, piggybacking research missions onto other existing studies that may be in locations, altitudes, or seasons that are not optimal for meeting AESA requirements.

Given its charge, AESA is obviously a directed scientific program. Consequently, several unique aspects of AESA distinguish it from a number of more general programs in atmospheric science research. Among them are the studies of the effects of atmospheric emissions occurring at high altitudes and within discrete flight corridors; the focus on plume dispersion and wake chemistry; the emphasis on stratospheric/tropospheric air exchange; and the implications of stratospheric aerosol injection and its effects at mid-latitudes. These aspects must be covered thoroughly by AESA, as they are not central topics in other atmospheric research programs.

The Principal Investigators involved in the AESA program include many scientists of extremely high caliber. Among their accomplishments are the development of data sets and scenarios for past and future aircraft emissions, laboratory studies of heterogeneous chemistry, and coordinated airborne measurements of key chemical species. Other programs within AESA show promise of producing results of direct usefulness to the program before 1995; these include the efforts in plume and wake modeling and in hydroperoxy (HO_2) and sulfur chemistry. In order to permit more conclusive results to be reached, NASA plans a continuation of HSRP beyond 1995.

THE NATIONAL RESEARCH COUNCIL ASSESSMENT PANEL

To provide an independent assessment of how well the AESA program is meeting the needs for which it was created, in late 1992 NASA requested the National Academy of Sciences' National Research Council (NRC) to establish a review panel. The charge to this Panel on Atmospheric Effects of Stratospheric Aircraft was to review the AESA Interim Assessment document and other program information and to address the following five questions:

1. Does the 1993 NASA HSRP/AESA Assessment accurately reflect the current state of scientific knowledge pertinent to HSCTs?
2. Have the key scientific uncertainties relevant to the atmospheric effects of stratospheric aircraft been identified?
3. Is the NASA/AESA program appropriately designed, within funding constraints, to reduce the key uncertainties?
4. Are there major research activities currently not funded that would

likely reduce the scientific uncertainties before 1995? (The 1995 date was specified because funding is currently approved through FY 1995.)

5. Will major scientific uncertainties remain after 1995? If so, what types of research efforts could significantly reduce those uncertainties within a few years?

Although the Panel on Atmospheric Effects of Stratospheric Aircraft was not formally established until January 1993, a number of members who would eventually be named to the panel heard a report of scientific progress in the HSRP at a workshop held in December 1992. In the course of performing its assessment the panel met five times:

- December 16-17, 1992, at the AESA Workshop in Boulder, Colorado, to receive initial overview information on the NASA HSRP/AESA program.
- February 9-10, 1993, at the NASA Lewis Research Center in Cleveland, Ohio, to receive presentations on the general themes of aircraft and engine design, engine emissions, and wake effects.
- April 22-23, 1993, at the NRC facility in Washington, D.C., to receive presentations on the general themes of relevant atmospheric chemistry, atmospheric measurements programs, and computer models of stratospheric impacts.
- June 7-11, 1993, at the HSRP/AESA Annual Meeting in Virginia Beach, Virginia, to attend presentations of AESA research results and to begin reviewing drafts of the panel's report.
- August 2-5, 1993, at the NAS Study Center in Woods Hole, Massachusetts, for discussion and work on the report.

OUTLINE OF THIS REPORT

The NRC Panel on Atmospheric Effects of Stratospheric Aircraft has chosen to evaluate the AESA program by discussing in Chapter 2 six scientific issues, as they are addressed by AESA and as they are viewed by the panel. In Chapter 3 the panel comments on the accomplishments of the AESA program: in particular, how successful AESA has been in identifying the key uncertainties relevant to HSRP and in implementing a directed program to resolve those uncertainties to the degree possible on the time scale of the program. Last, Chapter 4 presents recommendations for the time period 1994-1995 and for possible continuation of the program after 1995.

2

Scientific Issues Relevant to Evaluating Atmospheric Effects of An HSCT Fleet

This chapter presents discussions of six scientific issues related to HSRP: emissions and plume processing, homogeneous and heterogeneous chemistry, observations, transport and dynamics, other possible effects of HSCT effluents, and modeling. These issues generally correspond to chapters in the AESA Interim Assessment, except that the panel has combined two AESA topics (*Exhaust Characterization* and *Operational Scenarios*) and added two topics (*Transport and Dynamics* and *Other Possible Effects*).

HSCT EMISSIONS AND PLUME PROCESSING

Evaluation of the potential atmospheric impact of emissions from HSCTs requires a scientifically sound understanding of the nature and quantity of emissions from all prospective and existing types of aircraft and a knowledge of the operations of the total global aircraft fleet, in order to provide input to atmospheric models.

Emissions from aircraft comprise both those that are generated by the combustion process in the engine and those that are related to the airframe, such as the systems supporting flight operation or passengers. The exhaust emissions from the engines are expected to be dominant. These are functions of engine technology, of the operation of the aircraft on which the engines are installed, and of the fuel composition. It has also been recognized that a number of the dynamic and chemical processes that may occur in the engine exhaust plume and aircraft wake could significantly modify the emitted substances by the time they have been sufficiently dispersed to be regarded as inputs to the atmospheric models. Among these processes are entrainment of the engine exhaust plumes in the lift-inducing vortices of the aircraft, with possible resultant spatial localization of species and vertical transport of the partially mixed wakes; formation of sulfate aerosols; and generation of contrails.

Development of a comprehensive understanding for both current and future situations will thus require:

- Generation of appropriate fleet-operation scenarios for both subsonic and HSCT fleets
- Reliable estimations of emissions outputs and generation of a three-dimensional global emissions database for the chosen scenarios
- Development of a plume-processing model incorporating both dynamics and chemistry
- Validation of the plume model with measurements

Research into low-NO_x combustor technology for HSCT engines is being carried out in a program parallel to AESA within HSRP. Preliminary results from this program, in terms of minimum achievable levels of emissions, will be available only toward the end of the current HSRP time frame. Actual engines, and hence actual emission levels, will not be available until at least the end of the decade. As a consequence, a range of NO_x emission limits, spanning those likely to be imposed on HSCT engines operating at supersonic cruise conditions, has been chosen for use in the AESA program.

The assessment gives an excellent summary of the very comprehensive program of work undertaken to develop operational scenarios and to generate a three-dimensional emissions database. This program has included usage and regional distribution worldwide for all types of aircraft (scheduled, charter, cargo, military, turboprop, and more), and has taken into account anticipated passenger demand, HSCT cruise speeds and flight profiles, and city-pair networks. Prediction of aircraft-engine flight performance has been based on well-proven aerodynamic and engineering routines. Emissions have been estimated using widely accepted combustor correlations. Generic approaches have been taken where possible in order to simplify the possible combinations and make the computational requirements manageable.

In common with much of the rest of the AESA program, the emissions inventory's emphasis has been on NO_x. The current three-dimensional global emissions database (due to be delivered by the end of 1993) is limited to fuel burns and emissions of NO_x, CO, and total gaseous hydrocarbons. It represents one of the most comprehensive and realistic inventory projections ever developed. Moreover, from the fuel composition and combustion rate, emissions of CO_2, water vapor, sulfur, and perhaps particulate carbon (soot) can be estimated. More important, however, is that the methodology and framework required for such a database have been thoroughly developed, and will allow other operational scenarios and chemical species of relevance to HSCTs to be incorporated very easily. The species have been clearly identified and prioritized, as have recommendations for the development of advanced instrumentation for use in conjunction with the HSCT combustor research program. These instruments could provide realistic measurements of NO_y and particle characteristics, and would be important inputs not only to plume and wake models but also to chemical kinetics studies. It is therefore essential to keep to planned schedules.

Although the Interim Assessment report identifies a number of scenario issues that might be addressed (e.g., seasonality of operations, routing variations, and rate of introduction of HSCTs), they are expected to be second-order effects and to introduce only small improvements in assessments. However, sensitivity studies of these issues are perfectly feasible and could be carried out before the end of the current HSRP. Such studies would improve the overall understanding of the consequences of possible spatial and temporal variations of emissions input by HSCTs.

The plume-processing model being developed is based on aerodynamic studies that go back to the Climatic Impact Assessment Program of the 1970s. They have subsequently been extended, with experimental verification, by other programs and codified as UNIWAKE. However, UNIWAKE does not explicitly address either exhaust-gas entrainment into the wing vortex structure or the subsequent chemical or condensation processes. The current AESA program is addressing these issues, and the assessment gives a good summary of the approaches adopted.

One key issue is the nature and rate of formation of new particles by condensation processes within the plume. This has been recognized, but the appropriate theory is not yet sufficiently advanced, and appropriate measurements are sparse.

The plume/wake region is the key interface between aircraft emissions and the atmosphere. The chemical processes occurring here have the potential to strongly influence the nature of what is being transported and diffused away from the principal source, and will offer clues as to possible mitigation measures should they be needed. Thus, there must be a high degree of confidence in the understanding and quantification of the processes involved. The fact that all of this work is being carried out by a single group within AESA is therefore of concern, and consideration should be given to possible independent development of other models and to evaluation of work being undertaken elsewhere.

Experimental validation of the plume and wake evolution, i.e., a directed field measurements program, will eventually be necessary to provide confidence that the model accurately expresses the nature and level of those emissions. Such measurements are not anticipated within the current AESA program. However, some limited data on aircraft wake measurements do exist and should be used as a first step. Support should be provided for further experimental validation, possibly using wind tunnels.

HOMOGENEOUS AND HETEROGENEOUS CHEMISTRY

Our present understanding of the basic atmospheric chemical processes that would be affected by a fleet of stratospheric aircraft in the next century is somewhat reminiscent of the situation that prevailed in the 1970s, when the Climatic Impact Assessment Program's studies took place. Ozone-loss predictions varied enormously from year to year as advances were made in the measurements of key reaction rates and in understanding the different chemical cycles and their reservoir species. By the early 1980s the perceived seriousness of the stratospheric ozone problem had considerably diminished; small ozone decreases caused by chlorine released from chlorofluorocarbons (CFCs), rather than by gases released from the engines of stratospheric transports, were predicted to occur at some time in the twenty-first century. This false sense of security was rudely disturbed by the discovery of large ozone losses in Antarctica during the spring months. These losses were subsequently shown to be caused by reactions involving chlorine, after preprocessing of the inorganic chlorine and nitrogen compounds on surfaces of stratospheric particles (i.e., by heterogeneous reactions).

The potential ozone loss caused by the operation of a substantial fleet of stratospheric aircraft, as predicted by the present assessment, is reduced by the inclusion in the overall stratospheric chemical scheme of a very efficient heterogeneous loss of active nitrogen compounds (NO, NO_2, N_2O_5) to inactive forms (HNO_3) through sequestering N_2O_5 as HNO_3 by the reaction

$$N_2O_5 + H_2O \rightarrow 2HNO_3$$

The high efficiency of this conversion on liquid aerosol surfaces in the stratosphere greatly reduces the steady-state NO_x concentration and thereby reduces the effectiveness of O_3 removal by NO_x emitted from stratospheric aircraft. While clearly very important, these findings are not sufficient to establish the impact of HSCTs upon the atmosphere, since many other chemical processes are potentially important and other effluents must be considered.

To develop an improved quantitative assessment of the chemical processes coupling HSCT emissions to ozone and climate impacts, detailed information is required on the following: critical gas-phase reaction rate constants, phase equilibria of sulfate-water and nitric acid-water aerosol particles, and rates of reactions of chlorine-, nitrogen-, and sulfur-containing species on frozen or supercooled stratospheric aerosol surfaces. A significant portion of the AESA effort has been devoted to dealing with these issues.

The chemistry program associated with the AESA is of high quality and is being carried out by some of the most able laboratory scientists in the world. It has many features to recommend it and has already produced excellent science, particularly in the area of understanding multiphase processes at low temperatures. Detailed studies have addressed phase equilibria, the chemical mixtures giving rise to the formation of stratospheric hydrometeors, and the sensitivity of phase change within the hydrometeors to composition change of binary and ternary mixtures of H_2O, H_2SO_4, and HNO_3. The problem of supercooling of liquid forms is also addressed, although more studies are needed of non-equilibrium situations involving, in addition to nitric acid trihydrate (NAT) particles, possible metastable hydrates of nitric acid. There is substantial agreement in the findings, and differences in results between individual investigators are being resolved. The measurements can readily be incorporated into current models of stratospheric chemistry if one assumes, as seems reasonable, that the mixtures of $H_2O/HNO_3/H_2SO_4$ chosen to reproduce the atmospheric situation in the laboratory conform to reality.

The mechanisms and kinetics of some important heterogeneous reactions, such as $ClONO_2 + H_2O$ and $N_2O_5 + H_2O$, have also been studied in detail. The latter reaction has been shown to occur very efficiently on all likely stratospheric liquid aerosols, although it will not occur on dry aerosols.

Other important aspects of the chemistry of the lower stratosphere now need AESA emphasis. For example, in the absence of an effective NO_x ozone removal cycle, a large percentage of ozone removal in the lower stratosphere outside polar regions occurs by HO_x reactions. This means that the reactions of OH and HO_2 with stratospheric trace components must be re-examined in detail. Particular emphasis should be placed on the influence of water vapor concentration at low temperatures on these reactions. The role of unstable reservoirs for NO_x other than $ClONO_2$, such as HO_2NO_2 and organic nitrates, also needs to be considered. Careful laboratory measurements of photolysis rate coefficients for a range of molecules are needed as well.

Another concern has to do with the balance of studies between perturbed and unperturbed atmospheres. Recent analyses of the ozone problem have directed attention away from the NO_x removal cycle as a result of the high stratospheric aerosol loading caused by the Mt. Pinatubo eruption. At the lower aerosol loadings that were typical of much of the 1940s, 1950s, and 1960s, the N_2O_5 hydrolysis reaction could be less efficient, raising the possibility of greater ozone loss associated with HSCT operation than would be the case in the present atmosphere. This emphasizes the need for another look at the sensitivity of the $N_2O_5 + H_2O$ reaction rates and modeled HSCT influences on ozone to aerosol loading. The kinetics program also needs to take into account the chemistry of the upper troposphere, where organic molecules are more abundant. Studies could well be extended to include reactions involving organic as well as inorganic species, particularly organic nitrates.

A final area in which more effort is now appropriate is the heterogeneous chemistry of SO_2 in the presence of other reactants. In the troposphere SO_2 is oxidized mostly in water and/or aerosol droplets. The main oxidants are H_2O_2 and O_3. In the stratosphere an additional oxidant is hypochlorous acid, HOCl, whose gas-phase reaction with SO_2 proceeds at a rate that is diffusion limited. Reaction of SO_2 on stratospheric aerosols may slow the release of active chlorine from $ClONO_2$ and HCl reservoirs. Examination of this area is encouraged.

OBSERVATIONS

Cooperative observation programs have been conducted by AESA and the Upper Atmosphere Research Program (UARP) during the second Airborne Arctic Stratosphere Expedition (AASE II) and the Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE). In addition, future observations are planned during the Antarctic Southern Hemisphere Ozone Experiment (ASHOE) and the Measurements for Assessing the Effects of Stratospheric Aircraft (MAESA) program. Together, these programs represent a unique and impressive effort to reduce present uncertainties in understanding of the background composition of the lower stratosphere. The measurements have provided key data for AESA's purposes, including unprecedented information on O_3, ClO, BrO, OH, and HO_2, as well as on NO_x/NO_y, H_2O, and atmospheric tracers in the lower stratosphere. This part of the reported work is one of the essential elements for validating the assessment models.

Partly because of its timing and that of the field campaigns, the observations presented in the AESA Interim Assessment are limited largely to the major findings of the AASE II campaign. The assessment does not consider information obtained during other field campaigns that is relevant, even essential, to the HSRP, and does not explain the relevance of the planned SPADE and MAESA observations. It is not clear how the latter observations will be incorporated into the HSRP models, or whether steps will be taken to deal with unmeasured species or to narrow uncertainties.

The Upper Atmosphere Research Satellite (UARS) measurements of the global distribution of stratospheric aerosols and long-lived tracers should be particularly useful, and in fact analysis of all the available data is of comparable priority to new field campaigns.

The Interim Assessment report demonstrates that there are several gaps in the observational program: for example, the need to develop instrumentation to investigate the detailed composition and morphology of aerosol particles, to determine the concentration (in situ) of key chemical species such as $ClONO_2$ and N_2O_5, and to investigate dynamical processes in the lower stratosphere in greater detail. (The measurements of NO_y in the spring 1993 AESA/SPADE field experiments were an important step in this direction.) HSCT sulfur gas emissions and their effect on the stratospheric sulfur budget need to be examined further, and the major gaseous sulfur species, COS (carbonyl sulfide) and SO_2, should be observed. Also important to the HSRP are observations of the distribution as well as the spatial and temporal variability of stratospheric aerosols, and long-term measurements employing balloon or lidar techniques are critical to monitor the aerosol loading in the stratosphere. A northern high-latitude summer campaign is recommended, both because model results indicate that the largest local ozone changes from HSCT emissions occur during this season and because the dynamics at that time of year are relatively quiescent, which would make it easier to study the chemical balance issues that lie at the heart of HSRP uncertainties.

An important dynamical process that is not fully addressed in the assessment is the transport of tropospheric air into the stratosphere, particularly its temporal variation. It is essential for assessing the effect of aircraft emissions in this part of the stratosphere to know which portion of the air mass injected will reside in the lower stratosphere, and over what time period. UARS data should be useful in this context.

The HSRP/AESA observational program has not yet attempted in situ measurements in aircraft plumes or travel corridors, although a few accidental observations of aircraft emissions were made during SPADE. This program element needs expansion; it could emphasize chemical conversion in plumes and wakes, phase transformations in plumes and wakes, and the time and space scales of diffusion of the species emitted. Cooperation with European groups engaged in making such measurements would be fruitful. Published data obtained in recent U.S. and non-U.S. aircraft campaigns are also available, and effort expended in analyzing these studies might prove highly valuable. Once the modeling activities progress to the stage where plume and wake studies can be interpreted with confidence, plans should be made to track higher-flying supersonic aircraft, such as the Concorde or military aircraft. (This would probably require extra field campaigns.) Wind-tunnel studies of the chemical transformations in the plume could also be helpful.

TRANSPORT AND DYNAMICS

Except for some initial chemical and physical processing of the gaseous and aerosol emissions in the exhaust plumes and wakes of HSCTs, the evolution of these effluents and their reaction products will be governed by atmospheric transport and chemical processes. In particular, a portion of these species will be transported downward into the troposphere by stratosphere-troposphere exchange processes, and another portion will be transported zonally, meridionally, and vertically within the stratosphere. Proper assessment of these aircraft effects depends on both the photochemistry and the transport being used within the assessment models. The vertical transport is particularly crucial, in that the speed with which substances that are relatively nonreactive at lower altitudes move to altitudes where they are chemically transformed determines their atmospheric residence time. Horizontal transport is significant in that it can move trace gases to regions where their photochemical environment is very different (e.g., from low latitudes to polar night conditions). Finally, the dispersive action of dynamics is important, in that the rates of some chemical reactions depend nonlinearly on species concentrations.

The dispersal of gases and particles emitted from aircraft is an inherently three-dimensional (3-D) process. Among the atmospheric processes for which three-dimensional assessments are crucial is the modeling of polar ozone depletion, in which heterogeneous chemistry is initiated in regions where the temperature becomes colder than some critical value (e. g., where polar stratospheric clouds form). The airflow through these heterogeneous processing regions then leads to 'polar processed air." Both zonal and meridional flow are important parts of this processing airflow, and three-dimensionality is required to produce the temperature extremes properly. Three-dimensionality is important as well in determining the conditions that lead to the occurrence of extremely high concentrations of aircraft pollutants. These highest concentrations will tend to form in regions of low wind speed and small wind shear. A thorough understanding of stratosphere-troposphere exchange processes and their inclusion in models is particularly important for the proper assessment of aircraft effects. Since HSCT aircraft will deposit most of their effluents in the lower stratosphere, it is essential to determine the rate at which the various components leave the stratosphere and enter the troposphere, from which they will ultimately be removed by wet and dry deposition processes.

All the AESA assessments have been made with two-dimensional (2-D) models that use either residual or diabatic circulations; they are described in more detail in the Modeling section below. The concept is that the zonally averaged transport of chemical constituents can be represented by average north-south and vertical transport circulations, together with eddy-diffusion terms to represent the nonzonal effects that range in horizontal scale from planetary waves down to turbulence. The details of the transport specifications differ from model to model; two of the models include interactive dynamics (to some extent), while another uses specified temperature fields to derive the diabatic circulation; the other three use specified temperatures and winds. While there are some similarities in the transport circulations used in the six AESA assessment models, there are also differences. These six models are generally representative of the 2-D models that are being used for assessment of ozone depletion by CFCs and other interacting chemicals, although newly developed methods for parameterizing the effects of planetary waves in such models remain to be incorporated.

It is clear that the effects of a 2-D model's treatments of horizontal diffusion, atmospheric circulation, and vertical transport across the tropopause and the influence of these treatments on calculated HSCT-induced ozone changes need to be well understood. This need is highlighted by the Interim Assessment, which shows that ozone loss is more sensitive to NO_y increases at higher altitudes and, by implication, that the transport of injected material from flight level to higher altitudes is a key factor in determining the ozone loss. Changes in model circulation or mixing formulations that affect this transport should be studied, and observed values of tracers such as CH_4, N_2O, and aerosols used to constrain the realistic range of parameters.

A more systematic examination is needed of the reasons for differences in ozone depletion predicted by the several models, and to what degree those differences are explained by the parameterization of dynamics and transport. Although differences in transport circulation in models have been identified as one important source of the variability in the assessment models' results, no quantification of these differences appears in the Interim Assessment. Such assessments should be made. If, as expected, substantial differences in the assessment results are seen when differing circulations are specified within a given model, then a logical next step would be to vary the circulation throughout the extreme range that might reasonably be expected so as to obtain the extremes in the assessment results that would result from differences in the transport uncertainties alone.

A dual approach seems indicated for improving knowledge about dispersion near HSCT flight corridors. First, it is recommended that currently available satellite data and UARS data (including measurements of the Pinatubo aerosol) be used to obtain better estimates of the transport circulation. This has already been done to some extent, using heat budget calculations, "downward control" calculations, and long-lived chemical-constituent data, but more effort in this area is needed to obtain better assessments by 1996. Second, it would be advisable to consider aircraft flight experiments designed specifically to explore dispersion in atmospheric regions crucial to HSCT. Such experiments probably cannot be mounted prior to 1996, but may well be appropriate thereafter.

Two parallel strategies should be adopted for 3-D modeling between now and 1996. First, 3-D models should be used to evaluate the build-up of aircraft effluents, in order to estimate what extreme concentrations might occur. "Box," or zero-dimensional, models should then be used to investigate the occurrence of nonlinear or threshold effects. Second, at least one 3-D model should be used for ozone-depletion estimates in the 1995 assessment. It should be compared to a similarly constructed (in terms of chemistry and zonally averaged transport) 2-D model to analyze the differences that occur between 2- and 3-D assessments of HSCT operations. For instance, localized intense vertical transports might occur in 3-D models, so that greater O_3 depletions would occur in the 3-D atmosphere than would be modeled in the zonally averaged case. Also, as is recognized in the Interim Assessment report, transport through the mid-latitude "tropopause break" is not well modeled in the 2-D representations that are being used in the assessment, and the effects of synoptic-scale circulations are not represented in 2-D models at all. For all of these reasons, additional work, using 3-D models, should be started as soon as possible and used for the 1995 assessment.

MODELING

AESA Modeling Activities

AESA's primary tool for assessing the impact of a fleet of HSCTs on atmospheric ozone are six different 2-D (latitude and height) models of the atmosphere; some additional process-related studies have been carried out with 3-D models. They might be considered the capstone of AESA, since they synthesize the information from all other parts of the AESA program to make their predictions. Each modeling group has performed, at a minimum, calculations assessing the effects of six HSRP scenarios differing in Mach number, NO_x emission index, and background chlorine loading. The results have been presented largely as changes in annual average column content of ozone at different latitudes. The HSCT-relevant results listed below have been derived from this effort.

- For what has been presented as a median scenario, an HSCT fleet with emission index of 15 (i.e., 15 grams of NO_x emitted per kilogram of fuel burned) and Mach number 2.4, the column ozone depletion predicted by all of the models falls within the range of about 0 to 2 percent.

- The inclusion of the $N_2O_5 + H_2O$ reaction in the models decreases the importance of aircraft-related ozone loss, as it results in decreases in NO_x concentration.
- Because most of the HSCT flights will take place in the northern hemisphere, the calculated ozone changes are larger there than in the southern hemisphere.
- The calculated ozone loss is larger for higher emission indices of NO_x and for higher cruise altitudes.
- Of four principal species in HSCT effluent, NO_x and H_2O are much more important to stratospheric ozone depletion than are CH_4 and CO.

A second and commendable major effort of AESA related to models was the convening of a Models and Measurements Workshop, which attracted 14 different modeling groups, including all of those sponsored by AESA. Its goal was to investigate how well the models were reproducing relevant atmospheric data and how well the models agreed among themselves. Not all aspects of this goal were achieved, but a number of useful conclusions were reached. Two particularly valuable ones were that model results correlated reasonably well with measurements of long-lived gases in the winter stratosphere away from winter poles but were less satisfactory in the lower stratosphere, and that water injection and removal in the upper troposphere and lower stratosphere had not been effectively addressed by the models. Perhaps even more important, discrepancies among models were identified for increased attention. They included inadequate formulations of radiative transfer, inaccurate calculations of photolysis rates, and problems with the derivation of global circulations.

The AESA modeling activity needs to address and resolve all possible uncertainties associated with the models' predictions, given the time and resources available. From this perspective, the panel identified four topics related to modeling that are not currently emphasized and could benefit from increased attention. These topics are discussed in detail in the subsections below.

Differences Among Models' Ozone-Depletion Predictions

Although the inputs to the scenarios evaluated were the same, the various models yielded ozone-depletion results that differed in various degrees. These are illustrated in Figure 1. While the models are qualitatively similar (all predict increasing ozone losses for increasing NO_x emission index), they are quantitatively different (not only the absolute values but also the slopes of the ozone depletion as a function of emission index differ). For

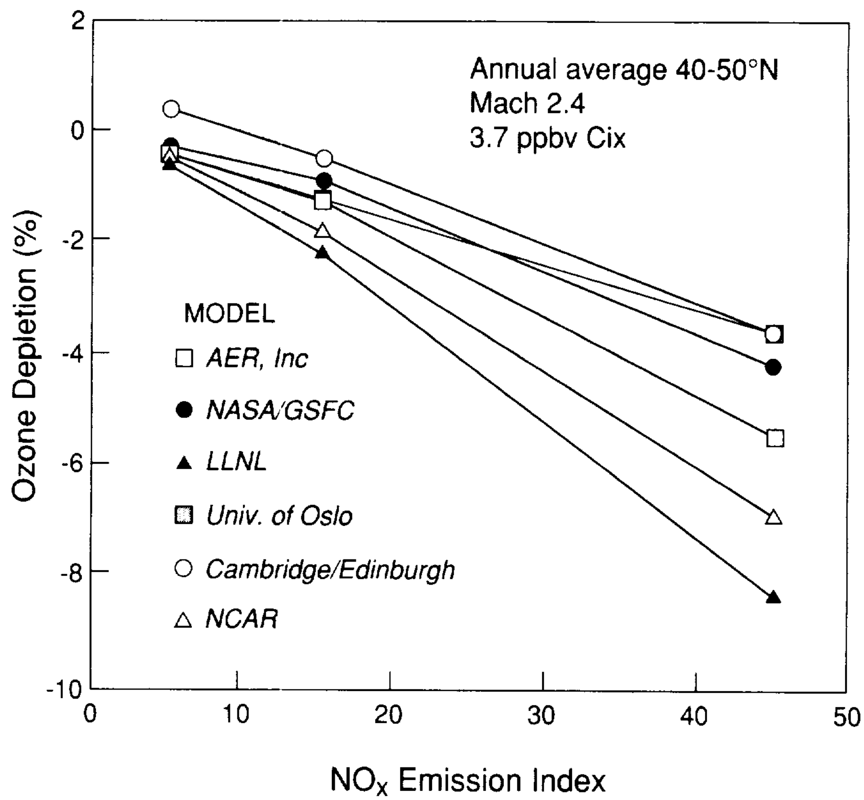

FIGURE 1 Calculated percentage of change in the annual average column content of ozone between 40° N and 50° N as a function of the NO_x emission index for an HSCT fleet in the year 2015.

example, while the absolute values of the computed averaged ozone changes in all of the models are below 3 percent for an emission index of 15, the values vary by more than a factor of three. These variations may result from differences in model transport, chemistry, numerics, or other factors. For example, the roles of the various effluent components (NO_y, H_2O, CO, sulfur, etc.) need to be probed individually and together, and the chemical reasons for any cancellation between them should be understood. The work to date focuses largely on NO_x injections, but notes that HO_x chemistry currently dominates the ozone budget of the lower stratosphere. It is critical to comprehend in detail how the chemical balance shifts as various components are injected, so that the relative efficiencies of the different catalytic cycles can be understood. Similar examples might be given for other potential causes of differing results. Until substantial progress is made in comprehending the reasons for these differences, it will not be possible to predict the impacts of an HSCT fleet on atmospheric properties with any confidence, or to assign uncertainties to those predictions.

One might begin by comparing at least two of the models in sufficient detail to understand the differences between them. Since transport formulations are a major difference between models that is difficult to assess, a useful approach might be to first compare the two models' chemical sensitivity to aircraft injections, using a prescribed chemistry, time of year, and initial conditions but including no transport. The results of such a comparison should be carefully documented and archived, so that there will be sufficient information for making the same critical comparisons with other models at a later time. Such explorations of differences between simulations would not only strengthen the conclusions by demonstrating mechanisms rather than simply giving results, but would also provide physical insights that should allow extrapolation of the findings to other conditions of interest. Once the chemical issues are better understood, the program could begin to address dynamical and numerical differences among the models. An approach of this type would be considerably more productive than running a large number of models to investigate further scenarios (e.g., other Mach numbers).

Tropospheric Chemistry

The NASA assessment report shows that the current estimates of potential column-ozone depletion due to HSCT flight represent a partial cancellation between ozone depletion above about 20 km and ozone formation below. It is therefore important to examine and compare not just the total ozone change in different models but also the vertical structure of ozone concentrations. The differences between models are due in part to differences in the location of the formation/depletion "crossover" point, and in part to the magnitude of tropospheric ozone changes. The organic chemistry related to these tropospheric ozone increases can be quite complex, and is probably not considered in detail in all of the HSRP assessment models. Furthermore, chemical species such as peroxyacetyl nitrate (PAN) are likely to be important. Implications for climate change and other effects may be present as well. A fuller evaluation of the assessment models' chemistry and of non-methane hydrocarbon emissions by HSCT aircraft is indicated.

Links Between Models and Measurements

A strong link is needed between the program activities in modeling and observing, both to permit identification of the successes and failures of the models (compared to the real world revealed through observations) and to guide further model development. Clearly, one source of data for such comparisons is aircraft data from campaigns of AESA and others. Additional useful information is available from observations from satellites, balloons, and ground-based platforms. Both U.S. and non-U.S. studies could be helpful. Among other campaigns, the upcoming European ozone study (the Second European Stratospheric Arctic and Mid-latitude Experiment, SESAME) may yield important new information on atmospheric chemical composition relevant to HSRP. Observations of long-lived tracers from UARS could also be used to evaluate the models' transport, especially in the mid- to upper stratosphere in the tropics. Ground-based measurements of O_3, NO_2, and OClO (chlorine dioxide) may also provide useful constraints on composition in certain regions.

A first step is provided by the AESA Models and Measurements report, but it is important to narrow the comparisons to specific issues that are of the highest relevance for HSRP. In several key areas, current observations reveal potentially important problems with the models. For example, some measurements suggest that the $HCl/ClONO_2$ ratios in the lower stratosphere might be very different from present model calculations. Also, the Models and Measurements report notes that nearly all current 2-D models display total ozone gradients that are weaker than those observed. This could imply excessive dispersion not only of background ozone levels but also of HSCT effluents, and thus perhaps result in an underestimation of HSCT-related ozone changes. A systematic comparison of HSRP models to measurements and a cataloguing of likely impacts on HSCT ozone-change estimates is needed.

Assessment of Uncertainties and Sensitivities

The Interim Assessment points out a number of possibly important factors (e.g., increases in sulfate aerosol content, changes in the distribution and frequency of polar stratospheric clouds, the nature of stratosphere-troposphere exchange, or limitations of 2-D models) that have not yet been assessed in detail. While a definitive evaluation of many of these issues is probably not within reach of the current models' capabilities, the range of possible impacts should be considered as sensitivity tests. Such sensitivity tests are critical to the key task of bounding the uncertainties on present calculations.

It should be noted that both chemical and dynamical uncertainties need to be evaluated. Some of the major chemical issues are discussed below, while dynamical questions were probed in the transport and dynamics section of this chapter.

Important uncertainties still exist in the area of aerosol chemistry and microphysics. Simulations should allow an evaluation of the possible importance of tropical stratospheric clouds (for which there is already some observational evidence). The possible importance of HSCT-related changes in water vapor on the sulfuric acid fraction in aerosols, and hence on chemical perturbations due to stratospheric flight, should be tested. In addition, several historical balloon aerosol data and results from modeling groups have recently suggested that the large-scale stratospheric aerosol content is altered by sulfur emissions from aircraft, and these emissions should be considered quantitatively in sensitivity tests. A related issue is the sensitivity of HSRP-related ozone changes to variations in background aerosol loadings in the stratosphere, particularly under volcanic conditions. Because higher aerosol loads lead to saturation of the N_2O_5 conversion to HNO_3, variations in background aerosols are likely to be quite important in determining ozone depletion in response to HSCT emissions.

The possible role of polar stratospheric clouds (PSCs) has been considered in only a preliminary way so far as ozone effects are concerned, and not at all so far as climate effects are concerned. The models should take into account the role of PSCs that form both within and without the polar vortex in HSCT-induced ozone depletion. Microphysical modeling is key to understanding the formation and chemistry of PSCs. Further work should be undertaken to narrow the uncertainties and to consider possible non-equilibrium phenomena (e.g., supersaturation) and their implications for HSRP assessment. An important aspect of these issues that has not yet been addressed is the linkage between the program's microphysical studies and the larger-scale 2-D models. It is also essential that the 2-D models begin to incorporate PSC phenomena, guided by the more detailed microphysical studies. This complex topic may well continue to require effort in the post-1995 time frame.

An additional key question is the likelihood of increases in the frequency of PSC occurrence because of the HSCT-related increases in NO_y and H_2O. If, for example, the latitude range of PSC occurrence were to be increased due to HSCT enhancements in NO_y abundances (particularly in flight corridors), the influence on ozone depletion could be quite large; these factors need not be restricted to local areas but could be transported over much of the hemisphere. Some studies have begun to examine this important possibility, but different groups have obtained substantially different results. The reasons for these differences need to be understood.

Other possible heterogeneous reactions should also be examined in greater detail. For example, the role of nitrosylsulfuric acid should be quantitatively examined, and its impact (or lack thereof) both physically explained and documented. Possible surface reactions involving formaldehyde, OH, and HO_2 should also be considered, both in flight corridors and over broader spatial scales.

The inputs of NO_x, H_2O, CO, and other effluents relative to background levels is another issue to be examined. For example, convective transport and lightning are likely to be important sources of reactive nitrogen injected into the lower stratosphere, and their magnitudes relative to N_2O oxidation and HSCT emissions may be important in determining the ozone depletion. The sensitivity of model results to various dehydration processes (e.g., the assumed tropical input mixing ratios and polar dehydration rates) would also be of interest.

The modeling studies might also productively consider a greater range of possible parameters that could affect the design or operation of the HSCT fleet. For example, it is clear that ozone depletion is sensitive to the altitude of the injection. Both higher (up to 25 km) and lower (down to 15 km) flight altitudes should be considered in order to determine whether there are threshold effects that must be considered. Indeed, the range of altitudes studied should not be constrained by current flight plans, but rather should reflect the scientific need to identify where such thresholds may lie. The possibility that HSCT emissions could perturb the number of particles present (at least locally) should be probed as well. If, for example, it were to be found that emissions of sulfur could significantly increase aerosol content and thus accelerate ozone losses, then detailed sensitivity tests would be a key factor for specifying fuel requirements.

OTHER POSSIBLE EFFECTS OF HSCT EFFLUENTS

This section deals with issues of concern to the panel that cannot appropriately be included in the other parts of this evaluation.

Climate

The importance of the potential effects of an HSCT fleet on climate has been recognized since the inception of the HSRP/AESA program. Indeed, this topic is called out as one of the motivations for the program in the initial Research Announcement. Nonetheless, the program has not thus far addressed the climatic effects per se, as is acknowledged in the Interim Assessment report. According to program management, this is the result of a conscious decision to concentrate the program's resources on the ozone problem.

The panel feels that the time has come to consider climatic effects. One possible effect is the influence of added water vapor on cirrus cloud and contrail formation. A marked increase in the frequency of these condensed phases could significantly alter infrared radiation transfer and local thermal structure, particularly in heavily used flight corridors and other accumulation regions. Another effect is the alteration of the number, size distribution, and cloud- and ice-nucleating properties of stratospheric aerosols as a consequence of HSCT emissions of particles and condensable vapors. The program should also consider possible climatic consequences of incremental changes in stratospheric and upper tropospheric water vapor concentrations (which can be as much as 40 percent, according to Table 1 of the Interim Assessment).

A further possible effect is an increase in the ozone content of the upper troposphere due to subsonic aircraft emissions in combination with a reduction in the lower stratosphere ozone content due to HSCT emissions. Such a situation could lead to a significant alteration of the thermal balance of the atmosphere. If this were to occur on a global scale, it might have one sort of impact, whereas on a local scale it might have quite another—for example, inducing vertical transport that might feed back to influence the ozone column, or perhaps vertical displacement of the tropopause. The potential revisions in AESA assessments that might result from greenhouse gas-induced changes in temperatures should also be considered. (Note that this point involves the impacts of changing climate on the HSCT assessment, rather than the effects of HSCTs on climate.)

These possibilities are of sufficient concern that the program should conduct an immediate first-cut assessment to ascertain whether further, more detailed study is required. By 1995 it should thus be feasible to report on potential climatic effects along with the effects on the ozone column.

Impact of Operational Constraints on the HSCT

One possible outcome of the HSRP/AESA program is that a HSCT fleet would be subjected to operational constraints in order to minimize its atmospheric impact. For example, limits might be placed on flight altitude and flight path. There is a precedent for such actions in the prohibition of supersonic aircraft overflight of densely populated areas in order to minimize sonic-boom impact.

An attempt has been made to include one such possibility in the AESA assessment by treating the flight Mach number parametrically, but there are many more ways in which the design parameters of an HSCT could be varied to meet environmental constraints while maintaining a viable transportation system. It is the sense of the panel that the responsibility for specifying such scenarios rests with elements of the HSRP program other than AESA. However, it would be desirable for AESA management to take the initiative to ensure that possible constraints are indeed studied by other elements, and that their results can be considered for incorporation into AESA model assessments.

Limitations to AESA Assessments

Given the complexity of atmospheric phenomena and the limitations of the present ability to model them, significant uncertainties remain as to the potential impact of a fleet of HSCTs on stratospheric ozone. As mentioned in earlier sections of this chapter, there are uncertainties because the atmospheric models do not completely represent the three-dimensional atmosphere. There are uncertainties in the representation of the physical and chemical processes, particularly those that take place on surfaces. For instance, soot may have the potential to catalytically destroy ozone, since it is well known that ozone decomposes on reactive surfaces such as charcoal. There are also some uncertainties about the actual composition of HSCT engine emissions and about their chemical modification and dispersion in the aircraft's wake. These uncertainties are of a major structural character, not capable of being described by quantifiable error bounds.

Although some uncertainties are inevitable, it is essential that the program reduce them to a minimum. It is equally important that they be described clearly and that their magnitudes be estimated. To the extent that atmospheric effects will constrain HSCT development and deployment, it is likely that decisions on emissions will reflect the conservative end of the uncertainty range. It is thus desirable that uncertainty estimates be kept as low as feasible.

Unexpected Phenomena or "Surprises"

Beyond the specific concerns already discussed, it is especially important that the program be conducted in such a way that all who are involved in it are alert to the possible existence of entirely new phenomena that have not been included in the models. Such phenomena might be found to modify the effects of HSCT emissions by a factor of ten or even more, rather as were found to enhance the effects of CFCs on ozone. In addition, there is the long-term possibility that shifts in the global climate may make the atmosphere more sensitive to HSCT effluents in the distant future than it is likely to be in the near future. Only a robust measurement and prediction methodology will make it possible to deal with this and other eventualities.

3

Program Management

NASA's Atmospheric Effects of Stratospheric Aircraft (AESA) program was established for the purpose of performing directed research in support of the High-Speed Research Program (HSRP). Since the program is concerned with the alteration of the upper troposphere and stratosphere, and since the general chemistry and dynamics of these regions are topics of vigorous scientific effort at present, the line between pure research and research directed toward the programmatic goals is not easy to draw. Nonetheless, it is clearly the intent of the sponsoring agency that AESA be more focused and less individually directed than might be a group of atmospheric research programs funded by the National Science Foundation.

In the view of the panel, the appropriate focus for AESA activities is to develop appropriate computer models and to resolve uncertainties in model calculations. This perspective means that the modeling program should guide the choice of field measurements and laboratory experiments. Commendable modeling activities have been carried out within AESA, but it is the opinion of the panel that scientific leadership within the program has generally resided on the field observations and laboratory experiment sides rather than on the modeling side, perhaps due to a programmatic emphasis on scenario evaluation. Studies with a clear link to model needs or to lines of research suggested by model studies should receive preferential treatment.

When the NRC panel was appointed, AESA had not compiled a prioritized list of key issues associated with the atmospheric effects of HSCTs.

The original Research Announcement (NRA-89-OSSA-16) indicated areas in which proposals would be welcome, however; they constituted an implied list of the key issues toward which program research was to be directed. Upon request of the panel, the AESA Program Manager provided more explicit information on the current and projected future goals of the program.

At its meetings and by correspondence, the panel generated its own list of key present issues, restricting the list to the "top three" and "next five". Those issues, and the justifications for so identifying them, are as follows:

Top Three Key Issues

- **Uncertainties in the dispersion characteristics related to effluents in the lower stratosphere.**

Justification: HSCT aircraft will inject reactive species into the lower stratosphere in well-defined flight corridors. The resulting effects will be determined to a great extent by the degree and time scale of effluent dispersion.

- **Effects of HSCT aircraft on climate.**

Justification: The anticipated perturbations in water vapor loadings and ozone vertical distribution suggest that climate effects may be important. However, no scoping study or more detailed work on this topic has been carried out under AESA.

- **Uncertainties in physical and chemical properties of stratospheric aerosols and PSC particles.**

Justification: Effects of condensed phases are important components of the HSCT assessment. In spite of pioneering work on the subject over 30 years ago, the compositions and morphologies of stratospheric aerosols remain poorly understood, and consequently the applicability of laboratory studies to stratospheric condensed phases thus remains undetermined.

Next Five Key Issues

- **Accuracy of emission levels and flight scenarios.**

Justification: Actual engines will be available about the end of this decade. Because the accuracy of the emission estimates will directly reflect the predictions of HSCT effects, every effort should be made to establish realistic estimates as soon as possible.

- **Uncertainty in modeling plume and wake chemistry and dynamics.**

Justification: The results from these models, still under development, will serve as input to the larger-scale atmospheric models. Work to date suggests that physical and chemical transformations in plumes and wakes may be important in determining far-field emission signatures.

• **Uncertainty in the adequacy of two-dimensional models for HSCT impact assessment.**

Justification: Much of the Interim Assessment relies on 2-D model results. However, many aspects of the HSCT impact assessment are inherently three-dimensional, and 3-D calculations need to be performed to guide and improve the accuracy of 2-D formulations.

• **Provision for adequate exploration of sensitivities of models to changed parameters.**

Justification: The assessment relies on models. It is therefore necessary to understand the model parameters to which the computed impacts of HSRP flight are most sensitive so as to maintain a realistic perspective on the model results.

• **Provision for dealing with surprises.**

Justification: As was shown in the case of the ozone hole, it is conceivable that important factors completely unanticipated by any of the AESA program activities could come to light. Contingency plans for measurement and modeling should include provisions for responding promptly to such eventualities.

Next, the panel compared its list with the Research Announcement's implied list and the AESA Program Manager's lists of current and projected (1993-1995) key issues. Although complete agreement on prioritization in such a complex scientific and technological project would be surprising, there are distinct areas of departure that merit discussion. In particular, in the opinion of the panel, gas-phase atmospheric-chemistry field measurements have been overemphasized by being designated as key issues, whereas the areas of aerosol particle observations and interpretation, dispersion, and especially model-sensitivity studies should have been identified as key issues early in the program and retained throughout.

Although several of the AESA program elements have definitely contributed to a reduction in key uncertainties, the program goals, as well as the plans for monitoring progress toward those goals, have not always been completely clear. As a result, allocation of funds has at times been inconsistent with the AESA key uncertainties. The AESA, as an applied science program, is responsible for providing an assessment of the potential atmospheric impacts of an HSCT fleet that is both credible and timely enough to offer maximum guidance to the aeronautics community. Fulfilling this mission requires that AESA objectives be clearly established and oriented to HSCT effects, that program elements be related directly to those objectives, that progress be actively monitored, and that the program be modified if appropriate. Much of the activity supported in AESA is of great intrinsic merit and contributes substantially to the general understanding of atmospheric processes, but significant portions of the work are not directed toward specific AESA needs and/or are not consistent with the 1995 timetable.

One example of this less-than-ideal allocation is the commitment of AESA funds to Perseus aircraft development. The Perseus program, while laudable from the point of view of atmospheric science, is unlikely to produce sufficient results germane to HSCTs within the 1993-1995 time frame to justify a large funding commitment from the AESA program. A second example is the AESA commitment to southern hemisphere aircraft campaigns rather than to studies testing the more active northern hemisphere flight corridors. This is not to suggest that pure science be ignored. The panel feels that fundamental research should be supported as far as is compatible with achieving the central purpose of the AESA program: to answer the driving questions within the requisite time. Indeed, a range of research is needed to understand processes more fully, to reduce uncertainties in conclusions yet to be derived, and to answer practical questions in time to be useful.

The panel recommends that specific goals be established and widely disseminated within the HSRP/AESA community, that scientists be sought to address critical areas of research for which suitable proposals are not forthcoming, and that goal realization and the monitoring of progress toward those goals be explicitly included as aspects of program management. To accomplish these tasks, we recommend an increase in hands-on guidance and coordination by the Program Scientist, which might require the expansion of this position to full time, and a change in the role of the Science Advisory Committee to that of a Scientific Steering Committee charged with more active program oversight.

4

Conclusions and Recommendations

This chapter summarizes the findings (detailed in Chapters 2 and 3) of the National Research Council's Panel on the Atmospheric Effects of Stratospheric Aircraft, and presents related recommendations. The panel reviewed the Interim Assessment report of the National Aeronautics and Space Administration's program on the Atmospheric Effects of Stratospheric Aircraft (AESA), as well as additional relevant information presented during panel meetings and other AESA program reports.

It is the panel's view that the impact of high-speed civil transport (HSCT) aircraft on the atmospheric environment can be evaluated only through models. A hierarchy of models is required, ranging from microscale to plume and wake-vortex to global two-dimensional and three-dimensional photochemical and dynamical models. All of these are being supported in greater or lesser degree by AESA. In addition, as a result of an impressive amount of work, aircraft emission scenarios for past and future aircraft emissions and detailed three-dimensional data sets are also available for NO_x and some other species. However, virtually all of the modeling effort has been directed toward assessment of the column depletion of ozone, a single measure of HSCT impact. While this is a crucial effect, it is not the only effect that needs to be investigated. The conclusions and recommendations below address this point and others that could enhance AESA's success.

The panel considers it essential that a clear picture of small-scale, localized processes in the wake and extended region behind the aircraft be obtained within the next two years. The immediate effects of HSCT emissions in the wake-dispersion regime will be described by a plume/wake model. Only one such model is currently under development, and it is still some distance from completion. Thus, important detailed results are not yet available, such as the distribution of SO_x, particle formation and evaporation, and plume chemistry.

> **We recommend** that AESA enhance this plume/wake modeling effort, and initiate validation studies using information recently obtained through aircraft wake measurements both within and without AESA. Additional measurements would be desirable, and wind-tunnel experiments should be explored as well. Plans should be made to incorporate plume model results into the larger-scale models.

The panel finds that an even more substantial database will be required to yield the reliable input parameters (including chemical composition, temperatures, and transport processes) needed to define the conditions of the background atmosphere for global models. The Upper Atmosphere Research Program and High-Speed Research Program aircraft measurements have provided key data for AESA's purposes, including unprecedented information on O_3, ClO, BrO, OH, and HO_2, as well as on NO_x/NO_y, H_2O, and atmospheric tracers in the lower stratosphere. A wealth of additional data that could provide information on composition and transport processes is available as well, particularly data derived from satellite measurements.

> **We recommend** that NASA incorporate satellite data sets into HSRP/AESA. The program management should organize the Upper Atmosphere Research Satellite data in timely fashion, particularly those on aerosol and atmospheric tracer measurements such as N_2O and CH_4, and make them available to the HSRP modeling community.

The panel commends the modeling community for including heterogeneous reactions on sulfate aerosols in the global atmospheric models that provided the set of ozone-change predictions presented in the Interim Assessment. Although the predictions of changes in ozone column burden agree reasonably well for low NO_x emission indices, they exhibit considerable unexplained differences for high values.

> **We recommend** that future modeling efforts include analyses of the differences between the predictions made by various models. Step-by-step comparisons for a limited number of models should be

initiated to obtain detailed knowledge about where and why differences arise.

The panel concludes that the single number produced by each of the six models to characterize the total ozone change is a useful initial measure for the present assessment, but this number does not indicate the range of uncertainty of the prediction. If uncertainties in model predictions of ozone column depletion are to be reduced in the near future, as indicated in the Interim Assessment, model performance must also be tested for realistic treatment of chemical constituents and of plume transport and diffusion.

> **We recommend** that for each prediction, an uncertainty range be calculated that carefully considers key unknowns in chemical and physical parameters, not only in kinetic rates. These ranges will determine the level of confidence in model predictions, and will thus serve as measures of the reduction of uncertainties as the modeling efforts progress.
>
> **We recommend** that assessments of HSCT impacts on ozone and climate consider the full range of possible aircraft effluents, particularly water vapor.
>
> **We recommend** that sensitivity studies of transport circulation become a part of model evaluations. Three-dimensional models will be useful as benchmarks for such an effort. Ranges should be selected with the aid of satellite and other data.

While the potential impact of polar and tropical stratospheric cloud particles on the distribution of ozone has been recognized in the Interim Assessment report, the panel notes that current AESA predictions do not take into account chemistry on frozen particulate surfaces within polar stratospheric clouds. A more advanced assessment of HSCT impact will require consideration of the chemistry of these clouds.

> **We recommend** that work on microphysical models be pursued to guide parameterization of microphysical processes in larger-scale models.

The panel finds that impressive progress has been made in heterogeneous chemistry in the laboratory under AESA sponsorship. Results from different groups for the reactions of N_2O_5 and $ClONO_2$ on sulfate surfaces have converged, and those processes have now been incorporated into global models. Surprises may still lie in wait, however. For example, the differences between the particle concentrations observed in the Arctic and the Antarctic stratospheres could be explained by the existence of metastable phases in nitric acid hydrate formation. Those phases could also play a role in the chemistry of high-latitude flight corridors.

> **We recommend** that future laboratory studies expand the range of species to include SO_x, organic molecules, and ternary systems. Laboratory studies should also explore non-equilibrium conditions for solid particle formation, in hopes of accounting for the presence of metastable phases and the sometimes extensive supercooling of condensable species.

The panel concludes that measurements of the composition and morphology of stratospheric aerosols and polar stratospheric cloud particles are still needed. We recognize that this is a challenging task, especially since suitable instrumentation is not flight-ready.

> **We recommend** that support for the development and field deployment of new instruments (perhaps a variety of them) be provided, to permit better physical and chemical characterization of particles.

The panel feels that the eruption of Mt. Pinatubo provided a unique opportunity to study the effect of aerosol loading on ozone abundance and heterogeneous processes. The background aerosol levels before the eruption and the tremendous increase after June 1991 clearly indicate the effects of the injection. Worldwide measurements showed the magnitude and dispersion of the aerosol cloud. While various studies of atmospheric changes following the eruption have been performed, an organized effort within AESA to review and analyze them could yield important information pertinent to the impact of an HSCT fleet. Some current models estimate that aerosols will increase by a factor of two above the background level when the fleet is fully operational.

> **We recommend** an extensive, coordinated analysis of the evolution of the Pinatubo aerosol cloud. This would provide important calibration and sensitivity benchmarks for models that predict future HSCT operation.

While the Interim Assessment acknowledges the possibility that the operation of an HSCT fleet might affect the climate, the panel finds that AESA has not adequately addressed its potential impact. Climatic changes could occur through perturbations in water vapor and resultant additional cloud formation, through formation of new aerosol particles, and through modification of atmospheric thermal structure (in turn affecting atmospheric circulation and possibly tropopause level) due to decreases of O_3 in the stratosphere and increases of O_3 in the troposphere.

> **We recommend** that AESA draw up a plan for careful evaluation of the nature and magnitude of potential HSCT-related climatic changes. While this area may require effort that continues beyond the 1995 time frame, the 1995 assessment must include possible changes in climate as well as in ozone abundance.

The panel is aware that HSRP has been managed with a minimum of personnel who were faced with the challenging task of directing activities ranging from laboratory studies to large-scale field measurements. The initial Research Announcement for solicitation of proposals specified general research areas, but did not list precise goals to be accomplished within a given time frame. Because such a list was never established, it has not been possible to monitor the progress that has been made in terms of specific HSRP-related goals.

> **We recommend** to HSRP management that the research over the next two years focus on the outstanding HSCT issues, particularly the potential impact on climate, the sensitivity studies of models, and the formation and dispersion of aerosols. Specific goals should be established and carefully monitored.
>
> **We recommend** as well that HSRP management consider increasing the hands-on guidance and coordination provided by the Program Scientist, perhaps to full time, and changing the role of the Science Advisory Committee to that of a Scientific Steering Committee charged with more active program oversight.

Chemical Formulae

BrO	=	Bromine monoxide
ClO	=	Chlorine monoxide
ClO_x	=	Reactive chlorine species
$ClONO_2$	=	Chlorine nitrate
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide
CH_4	=	Methane
HCl	=	Hydrochloric acid
HO	=	Hydroxyl radical
HO_2	=	Perhydroxyl radical
HO_x	=	Reactive hydrogen species (sum of HO and HO_2)
H_2O	=	Water
H_2SO_4	=	Sulfuric acid
HNO_3	=	Nitric acid
NO	=	Nitric oxide
NO_2	=	Nitrogen dioxide
NO_x	=	Reactive nitrogen species (sum of NO and NO_2)
NO_y	=	$HNO_3 + 2(N_2O_5) + NO_3 + HNO_4 + ClONO_2 + NO + NO_2$
N_2O	=	Nitrous oxide
N_2O_5	=	Dinitrogen pentoxide
O_3	=	Ozone
SO_2	=	Sulfur dioxide
SO_x	=	Reactive sulfur oxide species

Abbreviations and Acronyms

2-D	=	Two-dimensional (of models)
3-D	=	Three-dimensional (of models)
AER	=	Atmospheric and Environmental Research, Inc.
AASE II	=	Airborne Arctic Stratosphere Expedition II
ACMAP	=	Atmospheric Chemistry Modeling and Analysis Program
AESA	=	Atmospheric Effects of Stratospheric Aircraft program
ASHOE	=	Antarctic Southern Hemisphere Ozone Experiment
CFCs	=	Chlorofluorocarbons
GSFC	=	Goddard Space Flight Center
HSCT	=	High-speed civil transport
HSRP	=	High-Speed Research Program
LLNL	=	Lawrence Livermore National Laboratory
MAESA	=	Measurements for Assessing the Effects of Stratospheric Aircraft
NAS	=	National Academy of Sciences
NASA	=	National Aeronautics and Space Administration
NCAR	=	National Center for Atmospheric Research
NRC	=	NAS's National Research Council
PSC	=	Polar stratospheric cloud
SESAME	=	Second European Stratospheric Arctic and Mid-latitude Experiment
SPADE	=	Stratospheric Photochemistry, Aerosols, and Dynamics Expedition
UARP	=	Upper Atmosphere Research Program
UARS	=	Upper Atmosphere Research Satellite